1.9MWe Nuclear Electric Propulsion-Chemical Propulsion Piloted Mars Opposition Vehicle

Steven Oleson[1], Elizabeth Turnbull[1], Laura Burke[1], Thomas Packard[2], Lee Mason[1], James Fittje[3], Anthony Colozza[2], Paul Schmitz[4], Steven McCarty[1], John Yim[1], Brandon Klefman[1], John Gyekenyesi[2], Brent Faller[1], David Smith[2], Lucia Tian[1], Caroline Austin[1], W. Peter Simon[1], Christopher Heldman[1], Onoufrios Theofylaktos[1], Christine Schmid[1], Thomas Parkey[1], and Natalie Weckesser[1]

[1]*NASA Glenn Research Center, Cleveland, OH, 44135*
[2]*HX5, LLC, Brook Park, OH, 44142*
[3]*Science Applications International Corporation, Brunswick, OH, 44212*
[4]*Power Computing Solutions Inc., Avon Lake, OH, 44012*

Primary Author Contact Information: (216)977-7426, steven.r.oleson@nasa.gov

To assess 'quick' missions to Mars, a study was performed to determine the feasibility of a two-year roundtrip class mission concept of operation that enables boots on Mars in the 2030s. After performing a Phase 1.1 2036 Mars opposition design case, the more difficult 2039 opposition design was pursued. This Phase 1.2 also sought to further refine the concept, building on feasibility, and addressing several challenges brought by independent team reviews. Given the date of 2039, nearer-term technologies, primarily nuclear thermal and nuclear electric were deemed as the most viable for these missions. This paper explores a nuclear electric and chemical combined propulsion approach to achieve the desired mission timeline.

I. INTRODUCTION

Many previous studies have examined sending crews to and from Mars. The most economical involved a conjunction- class mission, whereby the crew spends around 500 days on Mars waiting for a 'cheap' return. The total mission time results in over a 1000-day mission duration (about 3 years). Given the current in-space crew experience level of only one year on the International Space Station (ISS), it of interest to reduce that time to only two years, thus reducing risk and minimizing required Mars surface infrastructure. The Phase 1.1 study[1] goal was stated as follows, "Determine the feasibility of a two-year roundtrip class Mars mission concept of operation that enables boots on Mars no later than 2036." While the Phase 1.1 study did show feasibility for the Nuclear Electric Propulsion (NEP)-Chemical option, the 2036 opposition-class mission opportunity was found to stress the schedule due to proposed technology development schedules. A 2039 opposition-class mission (which requires even more energy than the 2036 case) was chosen as representative for Phase 1.2. Phase 1.2 also sought to further refine the concept, building on the feasibility, and addressing several challenges brought by independent review teams.

Given the date of 2039, nearer-term technologies, primarily nuclear thermal and nuclear electric, were deemed as the most viable for these missions. As will be shown, the energy required to perform such a mission in only two years (for the 2039 opportunity at least) is about three times that of the three-year conjunction mission.

Based on lunar needs, a limit of five Space Launch System (SLS) launchers with 8.4 m fairings was imposed for the piloted transportation portion of the mission, limiting the size of the system. When using nuclear electric propulsion, the main limiting factor is packaging the required radiator area.

The higher specific impulse (I_{sp}) NEP system option is described herein, but with a twist: in order to keep the size of radiators packageable in one SLS and use proven reactor power system technology (~1200 K reactor outlet temperature and superalloy-class Brayton), the NEP system had to be combined with a chemical propulsion system. This combination of electric propulsion (EP) and high thrust chemical was found to be useful in previous design studies combining solar electric propulsion (SEP) and chemical propulsion[2]. Such a combination allowed the low-thrust system to provide a significant change in velocity (ΔV) during the interplanetary portions of the mission. This notably reduced the ΔV required by the high thrust system to capture and depart from the Mars gravity well, where the high thrust 'impulsive' system is more efficient due to the Oberth Effect[3].

A plethora of trades, both at the mission and system level, as well as the subsystem level were performed to develop these vehicle concepts. This paper highlights key design aspects of the 1.9 MWe Piloted Opposition Class Mission. However, far more detail is included in the final report[4], which outlines the full design, ground rules and assumptions. The final report also includes an entire family of NEP-Chemical transportation vehicles that use the same building blocks to reduce costs and provide commonality[4]. For example, there are many ways to use NEP-Chemical elements for cargo missions, such as using the main chemical stage to deliver one lander or using the NEP Module alone to deliver all three landers.
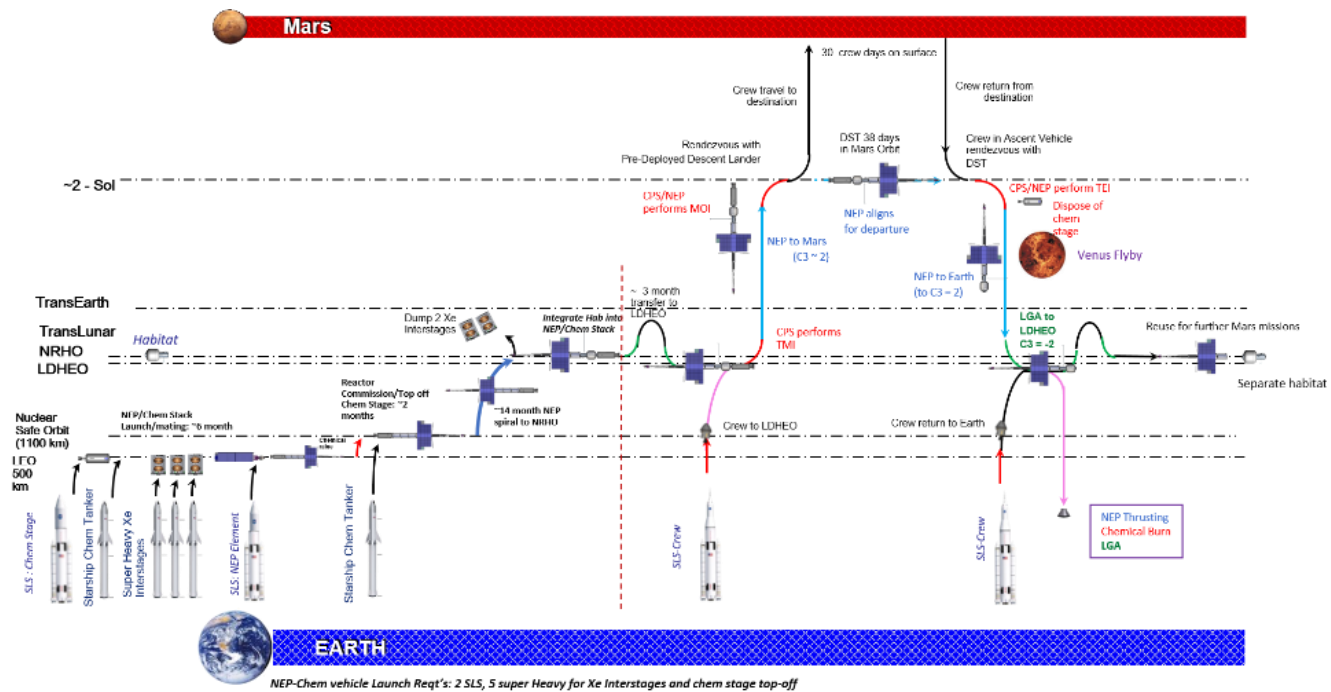
Fig. 1. Visual Representation of Mission Concept of Operations (ConOps)

II. CONCEPT OF OPERATIONS (CONOPS) AND MISSION DESIGN

Due to the multiple launch and staging nature of the NEP-Chemical vehicle, it is important to layout the concept of operations (CONOPS) to ensure all subsystems are sufficiently designed for all mission phases. The crewed vehicle CONOPS is described briefly below to support a piloted 2039 mission. A graphical representation is shown in Figure 1. The main in-space transportation elements were designed based on the requirements of this driving-case mission. Other mission options, for other year opposition and conjunction mission opportunities, are similar but may have fewer launches and elements and require less propellant. Additionally, an all-NEP cargo option and CONOPS is described in the appendix of the final report[4].

CONOPS phases are defined below for each specific element (NEP Module, Xenon Interstages, Chemical Stage and Habitat). Overall, the NEP-Chemical solution requires only two SLS launches and five super heavy commercial launch vehicles (CLV): three to carry the Xenon Interstages and two to tank up the Chemical Stage with liquid oxygen (LOx), and liquid methane (LCH4) propellants.

The assembly and fueling of the elements could occur in less than a year. The spiral out of the transportation system to near-rectilinear halo orbit (NRHO) (where it meets up with the Habitat) will take about 14 months, exclusively using the NEP system. This spiral will be a 'shakedown' cruise for the NEP-Chemical transportation system.

II.A. Launch and Assembly Phase (~ 6 months)

A 500 km, 28.5° low Earth orbit (LEO) was chosen for commissioning and fueling due to the benign qualities of limited orbital debris and no Van Allen Belt radiation. In addition, 500 km is a sufficiently low orbit to allow commercially launched crew to assist in assembly of the NEP-Chemical vehicle if needed. Only two SLS launches will be required: the NEP Module and the Chemical Stage. The Chemical Stage would be launched first, partially fueled, then the NEP Module would follow. A super heavy CLV will top off the Chemical Stage. Next, three super heavy CLV will launch three Xenon Interstages (carrying all the xenon required for the mission). Each element will have sufficient propulsion, power, and docking equipment to loiter at 500 km LEO and dock to the other elements. The NEP Module will deploy its reactor boom and electric thruster booms but will not start the reactor. This configuration is shown in Figure 2.

II.B. Boost to Nuclear Safe Orbit (1-2 days)

Once the NEP Module, three Xenon Interstages, and the Chemical Stage are docked, the Chemical Stage will perform two burns to lift the transportation stack to an 1100 km nuclear safe orbit. This phase is estimated to only take a day or two to complete.

II.C. Reactor Commissioning Phase in Nuclear Safe Orbit (1-2 weeks)

Once at 1100 km, two important activities take place. First, the Chemical Stage is undocked and refueled by another super heavy CLV. At the same time, the reactor will be started using the commissioning solar arrays for power. For startup, the reactor control system will actuate the control rods to achieve criticality (~1 kW for 1 hour) while powering the primary loop pumps to circulate the reactor heat. When a suitable temperature is achieved, the Brayton units will be individually motored to establish a self-sustaining condition (~2.5 kWhr for 4 hours). In parallel, the radiator loops will be charged, and the radiator pumps will start to circulate the coolant before the radiator panels are deployed. As reactor power is increased and more Brayton waste heat is generated, the panels will gradually deploy to match the desired radiator temperature. Once the reactor and the EP system has been checked out and the Chemical Stage has been refueled, they will be remated and begin a spiral to NRHO.
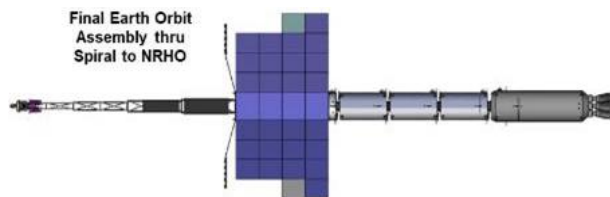
Fig. 2. NEP-Chemical Vehicle in Final Earth Orbit Assembly thru Spiral to NRHO Configuration

II.D. Spiral to NRHO (14 months)

The spiral to NRHO will exclusively use the NEP system for thrust, along with ~100 t of xenon. The integrated transportation system includes all the xenon and chemical propellants for the subsequent Mars mission, eliminating any fueling at NRHO.

The spiral from LEO to NRHO is not without impacts on the mission since it takes about 14 months and ~100 t of xenon. This almost doubles the required amount of xenon for the mission and increases the Hall thruster xenon throughput to ~13 t each. Use of a magnetically shielded design (based on the Advance Electric Propulsion System (AEPS) thruster) should allow this. Alternatively, additional thrusters could be added. An additional ~50 t of chemical propellant is needed to lift the NEP-Chemical vehicle to 1100 km before the reactor is started. This fuel requires an additional super heavy CLV 'top off' at 1100 km.

Two potential issues with the spiral include orbital debris and Van Allen belt radiation. By assembling the vehicle at 500 km and using micrometeoroid and orbital debris (MMOD) shielding on important components (such as radiator fluid lines, propellant tanks, etc.) the risk is minimized. The subsequent spiral from 1100 km to 2000

km (major orbital debris orbits) happens over a couple of months, which minimizes the risks. Tracking and avoiding major debris (similar to ISS operations) will also help reduce the risks. The Van Allen Belt radiation was assessed, and it was found that assuming 10 mm of shielding on the electronics (primarily by packaging most of the electronics inside the elements, near the propellant tanks) only 10 krad of radiation would be incurred.

II.E. Integration of the Habitat at NHRO (1-2 weeks)

Once in the NRHO, two of the nearly empty Xenon Interstages will transfer their margin and residuals to the three remaining single xenon tanks. Then, the chemical element will again be undocked and the two empty Xenon Interstages will be removed. The Habitat will dock in place of the removed Xenon Interstages and the Chemical Stage will reattach. This configuration is shown in Figure 3. The Habitat is assumed to be a free flyer already at NRHO and is outfitted for the Mars mission while the rest of the transportation system is spiraling to NRHO. Operational empty mass of the reusable habitat is 26.4 t with 20 kW of power required and a trash dump of 11.1 kg/day assumed during the transit to and from Mars.
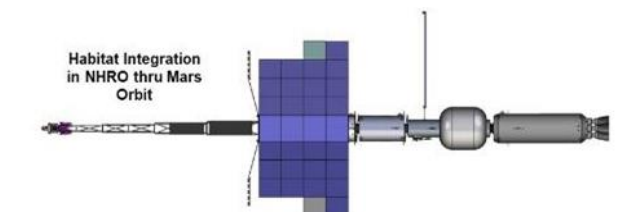
Fig. 3. NEP-Chemical Vehicle in Mars Transit Configuration

II.F. Mars Mission (~ 2 years) Phase:

The NEP-Chemical vehicle trajectory uses a hybrid propulsion system to perform a crewed opposition Earth-Mars roundtrip mission departing Earth on February 26, 2039 and arriving at Mars on December 11, 2039. Chemical engines are used at Earth and Mars to perform the major departure and capture maneuvers in the planetary gravity wells. The NEP system is used during the interplanetary transit to provide sustained acceleration which reduces the magnitude of the chemical maneuvers. This combination keeps transit times low by eliminating long spiral in and out maneuvers at Earth and Mars, and reduces the propellant load by limiting chemical ΔV.

Ballistic opposition missions have significant ΔV requirements, between approximately 6 and 10 km/s depending on mission opportunity. Using only a chemical propulsion system results in a vehicle of unrealistic mass due to the propellant load needed to perform the necessary ΔV. By using the NEP system during interplanetary transits, the ΔV that the chemical system needs to perform is reduced to roughly a third of the ballistic requirement. Since the NEP system is highly efficient the trade from

chemical ΔV to low-thrust ΔV saves a significant amount of total propellant.

The following propulsion system performance assumptions were made for the chemical and EP systems. The chemical system, modeled impulsively, assumed a LOx/LCH4 I_{sp} of 360 s nominally, but was modeled as 351 s to represent margin dumping following the burns. The EP system assumed a xenon I_{sp} of 2600 s, a 90 percent duty cycle, and a 59.4 percent efficiency.

Following a chemical trans-Mars injection (TMI) burn to escape Earth, the NEP system is active during the Earth to Mars transit. Prior to arrival at Mars the NEP system is shut down and the vehicle is re-oriented for the chemical system to perform the chemical Mars orbit insertion (MOI) burn to capture into an elliptical Mars orbit. Following an hour-long coast, an EP burn is used to refine the parking orbit further to achieve the 2-sol size and orientation to reach the 35° landing site. The actual size of the initial capture orbit following MOI is left open to the optimization process with an upper period limit of 10-sol. This limit was selected to reduce the capture sequence duration.

Following capture into the parking orbit, the crewed vehicle spends two orbits performing rendezvous, proximity operations and docking (RPOD) activities with the lander prior to descent. After successful rendezvous with the lander, two of the crew descends to the surface for thirty days to complete surface operations. After the crew ascends, they will spend two orbits completing RPOD operations with NEP-Chemical vehicle.

The crewed NEP-Chemical vehicle will then perform a short EP burn to align the vehicle to perform the trans-Earth injection (TEI) burn. After TEI is completed, the chemical stage is dropped along with any remaining xenon margin that was carried for the outbound transit. This configuration is shown in Figure 4. For 2039, the NEP-Chemical vehicle has not escaped Mars following TEI. Rather, TEI has increased the captured orbit size and the EP burn that follows it completes the Mars escape.
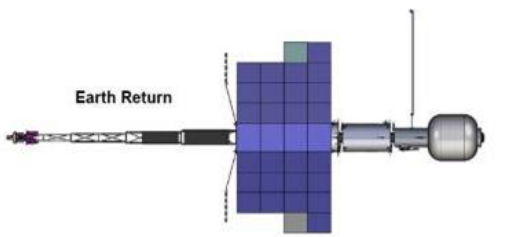
Fig. 4. NEP-Chemical Vehicle in Earth Return Configuration

The NEP system is used during the Earth-Venus transit and again following the Venus flyby. The Venus flyby is unpowered with multi-week coasting periods preceding and following. For the 2039 opportunity, there was a minimum flyby altitude of 2500 km. Once at Earth,

a series of lunar gravity assist (LGA) maneuvers are performed to re-capture into the lunar distant high Earth orbit (LDHEO). Minimum solar distance for this trajectory is 0.592 AU.

Once recaptured into the LDHEO an uncrewed Orion is launched to retrieve the crew. The NEP-Chemical vehicle then returns to NRHO using NEP and a weak stability boundary (WSB) transfer to return the Habitat for refit and potentially reuse of the NEP Module.

A more robust description of the mission design, trades, and history can be found in the related final report[4] and mission focused paper[5].

III. BASIC DESIGN

There are four main elements of which the Piloted Mars 1.9 MWe NEP-Chemical Vehicle is comprised: the NEP Module, the Xenon Interstage, the Habitat, and the Chemical Propulsion Module. The habitat will not be covered in this paper as it was provided to the team for this study and treated as a 'black box.' Figure 5 shows these elements in the vehicle configuration during its transit to Mars.
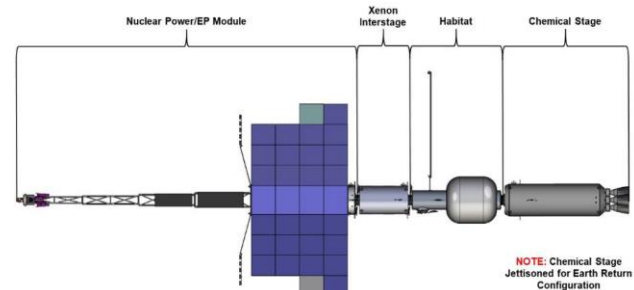
Fig. 5. The four main elements of the NEP-Chemical Vehicle

The 1.2 NEP-Chemical conceptual design solved several issues with the previous iteration. The tanker fleet was reduced in this version by assembling and fueling the vehicles in LEO and then using the vehicle to lift itself (with all the required propellants) to the NRHO where the Habitat element is integrated. Compared to the previous design, starting in LEO reduces the CLV launch fleet from ~30 heavy CLV down to only five super heavy CLV (or an estimated ten heavy CLV).

III.A. Spacecraft Mass Summary

The mass summary in Table I captures the bottoms-up current best estimate (CBE) and growth percentage of the NEP-Chemical vehicle elements. To meet the American Institute for Aeronautics and Astronautics (AIAA) mass growth allowance (MGA) and margin recommendations, an allocation is necessary for margin on basic dry mass at the system-level, in addition to the growth calculated on each individual subsystem component[6]. This additional system-level mass is included as part of the inert mass to

be flown along the required trajectory, therefore impacting the total propellant required for the mission design.

A representative mass for a re-entry shield for the reactor is included in Table I. This is carried from launch until the spacecraft reaches a nuclear-safe orbit. At that point, the re-entry shield is dropped.

TABLE I. Summary of System Level Mass by Design Element

|	NEP Module (kg)	Xenon Interstage (kg)	Chemical Module (kg)
Nuclear Power	25,684	0	0
AD&C	72	102	74
C&DH	79	48	49
Communications	42	55	42
Electrical Power	462	236	361
Thermal Control	1,192	705	869
Chemical Propulsion Hardware	428	399	10,152
Chemical Propellant at Launch	3,086	1,511	77,866
EP Hardware	9,294	3,715	0
EP Propellant at Launch	26,029	84,343	0
Structures and Mechanisms	6,507	2,527	4,015
Element Dry Mass	43,761	7,786	15,563
Element Propellant at Launch	29,115	85,854	77,866
Element MGA	7,678	1,227	2,442
Element MGA percentage	18%	16%	16%
15% Mass Margin	6,564	1,168	2,334
Re-entry Shield	1,000		
Dry Mass incl. all Margins	59,002	10,181	20,339
Inert Mass incl. all Margins	63,103	10,500	24,112
Wet Mass at Launch incl. all Margins	88,117	96,035	98,205

III.C. NEP Module Design

For Phase 1.2 the reactor and EP systems were combined in a single element, except for the additional xenon tankage, which is provided by the Xenon Interstages. The main driver for this merging was a ground rule to not pass power or propellants through the Habitat. It also eliminated the potential interaction between the NEP thruster plumes and the Habitat systems.

The first option was to put the thrusters on two long booms to try and eliminate the sputter and deposition impact from the electric thrusters. Analyses showed that this would be problematic and would constantly change as the Habitat design changed. Next, a concept to pass power around the Habitat by deploying cables or using an arm was discussed but again, it would require interface/interactions with the Habitat.

In the end, the electric thrusters were placed on the nuclear power element facing back towards the reactor. Analyses showed that with a 1 mm layer of pyrolytic

graphite on the boom, the sputter and deposition (back onto the radiators) would be minimized. This approach also removes constant changes in the EP system as Habitats, or indeed other cargoes, are integrated to the NEP Module. The NEP Module becomes a complete power and propulsion system ready to push Xenon Interstages, Habitats, landers, Chemical Stages, or whatever is needed. This creates an all-in-one NEP vehicle (albeit launched with limited xenon propellant, ~44 t). In addition, there are no high power or coolant lines to other docked elements required. The main drawback is that reuse of the NEP Module will be more challenging if thruster changeout is needed for subsequent missions.
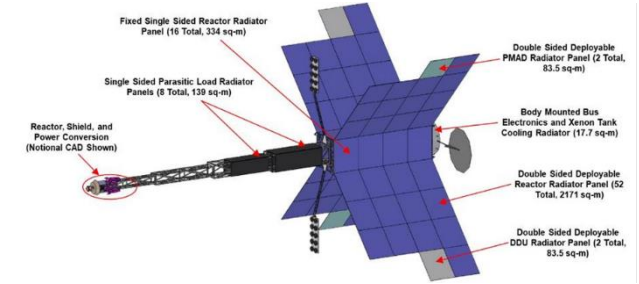
Fig. 6. NEP Module with External Components Noted

Given the combining of the nuclear power and electric propulsion into one element, only a single xenon tank could be carried (~44 t of xenon) on that element. Thus, additional xenon will need to be carried – more for some missions than others. The Xenon Interstage element was the solution to this. Two large carbon overwrap pressure vessel (COPV) tanks in one Xenon Interstage allow launching almost 85 t of xenon in a dockable, free flyer element using a super heavy CLV. For the 2039 mission, three Xenon Interstages are needed, but two are dropped after the spiral to NRHO so their empty tank mass is not carried to Mars and back.

For the NEP Module to fit within the fairing, several components must be stowed for launch and deployed once delivered to the appropriate orbit. These components include the nuclear power system (reactor, shield, and power conversion), the parasitic load radiators, the reactor radiator panels, the reactor power management and distribution (PMAD) radiator panels, the direct drive unit (DDU) radiator panels, the EP thruster booms, and the solar array used for commissioning power.

The array is deployed first so it can provide the commissioning power for deployment of all the other components as well as provide power for startup of the reactor. Deployment of the nuclear power components is performed by a telescoping boom that extends these components out and away from the bus. This not only allows the module to fit within the fairing when stowed, but also, provides at least a 50 m distance between the base of the reactor shield and the reactor PMAD electronics located inside the aft end of the module (minimizing their

radiation exposure), and allows the deployed radiators to fit within the radiation shield cone provided by the reactor shield.

The reactor, reactor PMAD, and DDU radiator panels are mounted to a box truss that surrounds and ties into the bus structure and the outer most (fixed) truss section of the telescoping boom. Combining the fixed, single sided radiators with the deployable radiators there is a total effective radiator area of 2500 m^2 for the reactor heat rejection. The double-sided radiator panels are stacked to allow the radiators to remain within the 26° radiation shield cone when deployed.

Each of the two EP thruster booms consists of two boom sections that provide a total boom length of 6.88 m. At the end of each of the thruster booms is a two-axis gimbal that will gimbal a thruster platform that contains ten 100 kWe Hall thrusters and ten low pressure xenon flow controllers (one per Hall thruster).

The bus for the NEP Module is located inside the radiator box truss opposite the reactor. The bus is a cylinder that provides the structure to mount the fixed truss portion of the telescoping boom and the box truss containing the reactor radiators. The bus also provides the interface to the payload launch adapter (PLA) at launch. A small section of the cylindrical bus structure extends out from the end of the radiator truss to provide area for the bus avionics, the attitude determination and control (AD&C) system, the monomethyl hydrazine (MMH)/ nitrogen tetroxide (NTO) reaction control system (RCS), and the international docking system standard (IDSS)-based docking systems (see Figure 6). The NEP Module is the passive docking element, while the Xenon Interstage will be the active element.

### III.C. Xenon Interstage Design
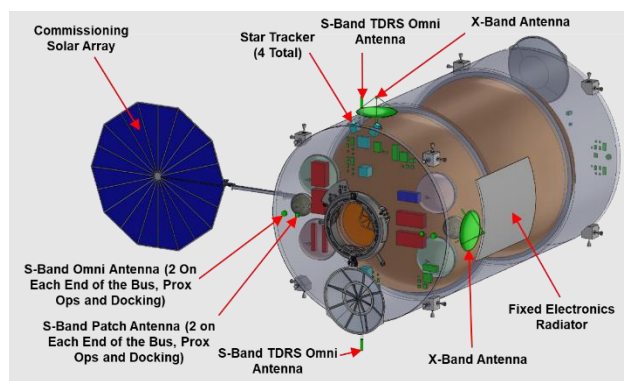
Fig. 7. Xenon Interstage Module, External and Internal Views

The Xenon Interstage is a free-flyer xenon tanker that can be integrated into the vehicle flight 'stack' and disposed of as needed. Figure 7 shows the external avionics, RCS, AD&C, power, thermal and docking systems. Note that docking systems exist at both ends of

the interstage to allow for in-line docking of several interstages. The docking adapter also allows for low pressure xenon transfer to the NEP Module.

III.D. Chemical Propulsion Module Design

The final element is the Chemical Stage, which can be topped off and refueled on-orbit for the 2039 mission. Due to the ~200 t propellant load, the SLS was chosen as a representative way to launch the chemical stage for the mission. The stage could be also be topped off using super heavy CLV (especially for CLV that use the same propellants). For some easier opposition and conjunction missions, the 200-ton stage might be oversized, and smaller stages could be used. This suggests that using multiple stages for even the 2039 opposition mission is possible but integrating those stages was outside the scope of this study. In addition, given the commercial capabilities of chemical stages, it is recommended that other chemical stage configurations be explored.
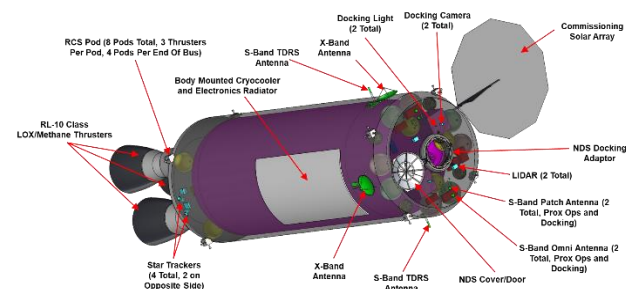
Fig. 8. Chemical Propulsion Module, External and Internal Views

The Chemical Stage is a long duration, dockable, free flying LOx/LCH₄ stage that provides the high thrust burns both at Earth and Mars. It also provides sufficient cryocooler systems to eliminate propellant boiloff and is refuellable.

The bus structure for the Chemical Stage is comprised of a long cylindrical tube with a conical section and endcap at one end that reduces the diameter down to the interface diameter of the PLA, and another conical section and endcap at the other end that acts as the thruster structure for the main chemical thrusters. The diameter of the bus structure was driven by the 5 m diameter of the chemical propellant tanks contained inside. A common bulkhead tank design was utilized to ensure the tanks could carry the required propellant loading while allowing the chemical stage to fit within the payload fairing.

The external communications, AD&C system, IDSS derived docking mechanism and MMH/NTO RCS systems of the Chemical Stage are shown in Figure 8. Note that the lidar units, cameras, and lights are required as the propulsion module is always the active vehicle when docking to the full NEP vehicle assembly. Sufficient tank insulation and active cryocoolers with power and radiators

are supplied for maintaining zero-boil-off for the LOx and LCH$_4$ propellants.

IV. SUBSYSTEM HIGHLIGHTS

The NEP-Chemical vehicle elements are each fully capable, free-flyer spacecraft to allow for separate launch, vehicle self-assembly by docking and element 'staging' by undocking as needed. To be brief, only the nuclear power system (reactor/ power conversion / radiator), the EP system, and LOx/LCH$_4$ propulsion and cryogenic storage systems are described here. A complete description of the many subsystems is provided in reference 4.

IV.A. Reactor, Power Conversion, and Heat Rejection Systems

The fission power system is the major element of the electrical power subsystem. NASA has pursued nuclear fission power many times in its history due to the attractive features of the technology, namely its high power density and capability to operate independently of sunlight. NEP systems have been studied over a wide range of power levels and use cases. A recent concept study, performed in 2012[7], targeted 2.5 MWe using a reactor core based on highly enriched uranium nitride (UN) fuel studied under the SP-100 program. This reactor power system used a pumped liquid metal loop to transfer heat to a helium xenon (HeXe) Brayton power conversion system. Since this study, significant progress in the field of space nuclear fission technology was achieved through the NASA Kilopower[8] project.

The major design considerations for sizing the power of a nuclear electric system are the reactor core design, the heat transfer method, the power conversion system, and the heat rejection system. Core design, while complex from a nuclear engineering standpoint, can be viewed simply as determining the temperature provided by the heat source. The uranium molybdenum (UMo) Kilopower fuel was designed to operate at 1100 K, while the 2012 concept was designed for 1500 K operation. As with any thermodynamic cycle, the heat source temperature plays an important role in system efficiency and specific mass. Higher temperature reactors are desirable from a mass perspective but are less mature and more difficult to test and therefore lower on the technology readiness level (TRL) scale.

Secondly, heat transfer plays a major role in system design and reliability. The three major primary heat transfer methods for cooling space reactors are heat pipes, pumped liquid metal, and pumped gas. Though all these methods involve some sort of fluid motion, the mechanisms differ significantly. Heat pipes work on a passive two-phase evaporation/condensation cycle that requires no external power, while liquid metal or gas cooling requires drive pumps or compressors to actively circulate the fluid.

The final major design decision is the power conversion system. The typical options include the Stirling, Brayton, and Rankine thermodynamic cycles, as well as thermoelectric and thermionic devices. Each option presents different characteristics on thermal efficiency and power throughput, and therefore on the system mass. A supercritical carbon dioxide (scCO$_2$) (or perhaps other supercritical working fluid) Brayton system was baselined for this study due to its progress for terrestrial applications and is shown in Figure 9.
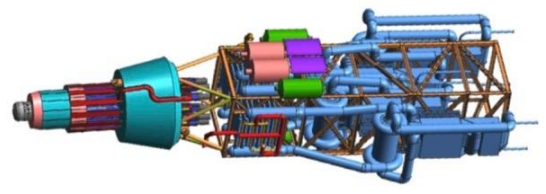
Fig. 9. NEP Reactor-Brayton Configuration

The vacuum of space requires radiative heat rejection, which is dependent on large, bulky radiators. In fact, the limiting design factor for the fission system in this study was the stowed radiator volume that could be accommodated in a single launch vehicle. Preliminary radiator stowage concepts have indicated a maximum radiator area of approximately 2500 m^2 for the 8.4 m SLS fairing. The benefits of the high temperature reactor studied in 2012 were increased efficiency and higher heat rejection temperature, both of which contribute to a decrease in the radiator area required for a given power level. The heat rejection subsystem for the current reactor concept assumes that each Brayton converter has a dedicated pumped-sodium potassium (NaK) cooling loop and a one-fourth segment radiator assembly. The NEP radiators would operate at temperatures between 375 and 550 K. This temperature regime was studied extensively during the NASA Prometheus Project[9] and follow-on Fission Surface Power Project[10]. Leveraging these studies, the NEP radiators use polymer-matrix composite (PMC) panels with embedded Ti/H$_2$O heat pipes. The 2500 m^2 total NEP radiator surface is comprised of four radiator segments each having 17 individual radiator panels (approx. 4 m x 5 m) that are coupled to the NaK coolant manifold.

IV.B. Propulsion

The propulsion system for this design consists of three independent systems that work together to provide the vehicle with its required ΔV capability and controllability, with the EP and RCS systems being interconnected across multiple modules. The main propulsion system is based on 100 kWe class Hall thrusters utilizing xenon propellant. The other two systems are a high thrust system based on LOx/LCH$_4$ being used for departure and capture maneuvers, and an MMH and NTO based RCS used for attitude control.

The EP system is designed around 100 kWe Hall thrusters that are mounted on gimballed pallets located at the end of deployable booms. These pallets are orientated so that the Hall thruster plumes are projected toward the reactor and away from the rest of the vehicle. There are twenty Hall thrusters in total, ten on each pallet, that are in an 18+2 configuration. These thrusters are magnetically shielded, have a nominal I_{sp} of 2,600 s at 600 V with xenon propellant, and are a single channel design with a center mounted cathode. The thrusters have an estimated propellant throughput capacity of 13.5 t, which equates to approximately 22,000 hours of operation. These thrusters are based on previous high-power designs that have already been developed, such as the NASA 457 Hall thruster. Interaction of the thruster plume with the vehicle is an important design aspect and is covered in the full report.

The xenon propellant for the Hall thrusters is stored in seven identical door-knob shaped tanks, one on the NEP Module and two on each of the Xenon Interstage Modules. The tanks are COPVs with a titanium alloy liner, T-1000 overwrap, and a mounting flange at the equator. They are sized to hold the largest quantity of xenon required on the NEP Module during the mission, which is estimated to be 44.2 t and which exerts 7.6 MPa on the tank walls at 300 K.

The Chemical Stage is used for large ΔV maneuvers that must be completed within a narrow time window, and thus require a much higher thrust level than delivered by the EP system. The high thrust comes from LOx/LCH₄ based engines, with the cryogenic propellant stored in a single common bulkhead tank.

The thermal control for the LOx/LCH₄ cryogenic system is a major aspect of the overall thermal design for the Chemical Stage. In-space cryogenic propellant storage is a newer technology that is still under development. Although cryogenic fuels are commonly used with launch vehicles, their use in space has been limited and long-term storage of cryogenics in space has not been previously accomplished. The heat leak into the tanks must be removed to maintain the propellant in its cryogenic state. This heat removal is accomplished through the broad area cooling system consisting of cryocoolers and a coolant loop that surrounds the tanks. The cryocoolers cool the helium gas to the desired operating temperature of the tank. A pump is used to move this coolant through tubes that surround the tank. Outside of this broad area cooling system is a combined multilayer insulation/micrometeoroid protection system which minimizes the heat leak into the tank.

V. CONCLUSIONS

The Phase 1.2 design provided several improvements over the Phase 1.1 design while completing the more demanding 2039 opposition opportunity. The same two-year mission was achieved by slightly increasing the EP power from 1.5 to 1.8 MWe as well as increasing the amount of ΔV and propellant from the Chemical Stage. When applying the same NEP-Chemical vehicle to different missions, it will be arguably easier to change the Chemical Stage propellant load rather than changing the power level of the EP system. For conjunction missions, the stage could be much smaller, and for non-time-critical cargo missions, the chemical stage could be eliminated altogether[4].

Phase 1.1 ground ruled launching all stages and propellants to LDHEO for assembly. Phase 1.2 instead allowed for assembling and commissioning the NEP-Chemical components in LEO and spiraling the fueled vehicle (uncrewed) to the LDHEO departure orbit. By using the high I_{sp} NEP system to get to the LDHEO assembly orbit, the launch fleet was reduced from ~30 heavy CLV down to only five super heavy CLV (or an estimated 10 heavy CLV) as compared to the Phase 1.1 concept. The increase in xenon (especially for the spiral from LEO to LDHEO) was addressed by the creation of the Xenon Interstage element.

The other major configuration change from Phase 1.1 was the merging of the nuclear power and EP systems into one module. This eliminated the need to pass MWe of power and xenon across the Habitat. The electric thrusters were also pointed back along the reactor boom (with proper anti-sputter carbon shielding) to alleviate any electric thruster plume impact on the Habitat.

Phase 1.2 completed the two-year piloted opposition NEP-Chemical concept studies. Future work will trade softening the two-year trip time and trading all-chemical and SEP-chemical approaches.

ACKNOWLEDGEMENTS

REFERENCES

1. S. OLESON et al, "A Combined Nuclear Electric and Chemical Propulsion Vehicle Concept for Piloted Mars Opposition Class Missions," *ASCEND 2020*, Virtual Event (2020).

2. M. L. MCGUIRE et al., "NASA GRC Compass Team conceptual point design and trades of a hybrid Solar Electric Propulsion (SEP)/Chemical Propulsion Human Mars Deep Space Transport (DST) Vehicle," *2018 AIAA SPACE and Astronautics Forum and Exposition*, Orlando, FL (2018).

3. H. OBERTH, Ways to Spaceflight, English language translation of the German Language Original "Wege zur Raumschiffahrt" ed., Tunis, Tunisia: *Agence Tunisienne de Public Relations*, 1970 (1920).

4. S. OLESON et al., "Compass Final Report: Nuclear Electric Propulsion (NEP)-Chemical Vehicle 1.2", *NASA Technical Reports Server*, Cleveland, OH (2021).

5. L. BURKE, "Combined Nuclear Electric and Chemical Propulsion for Crewed Mars Opposition Missions," *NETS*, May 2022, Cleveland, OH. *(Pending Acceptance)*

6. AIAA, "Standard: Mass Properties Control for Space Systems (ANSI/AIAA S-120A-2015 (2019))," *AIAA*, Reston, VA (2019).

7. M. LAPOINTE et al., "MW-Class Electric Propulsion System Designs for Mars Cargo Transport," *AIAA SPACE 2011 Conference & Exposition*, Long Beach, CA (2011).

8. NASA, "Space Technology Mission Directorate - Kilopower," *NASA*, (2021).

9. R. TAYLOR, "Prometheus Project: Final Report," *Jet Propulsion Laboratory*, Pasadena, CA (2005).

10. D. PALAC, "Fission Surface Power Systems (FSPS) Project Final Report for the Exploration Technology Development Program (ETDP)," *NASA Glenn Research Center*, Cleveland, OH (2011).